Why Search for Primordial Non–Gaussianity?
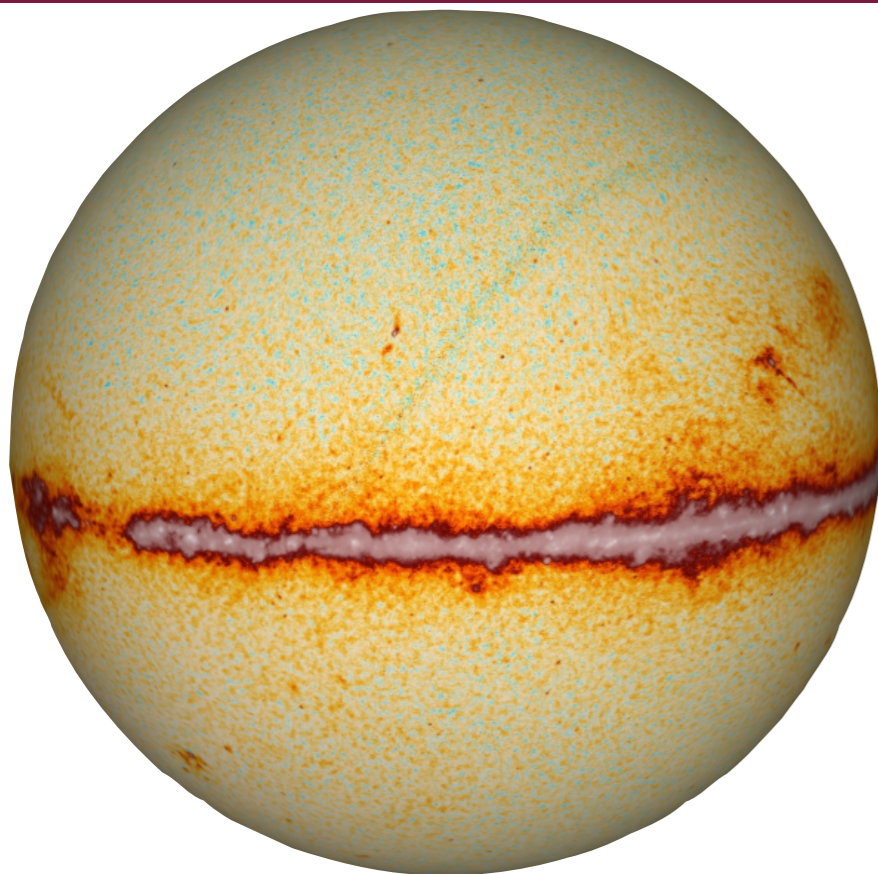
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Courtesy of thecmb.org

What are we testing?

What are the limits after Planck?

What does this mean for Inflation?
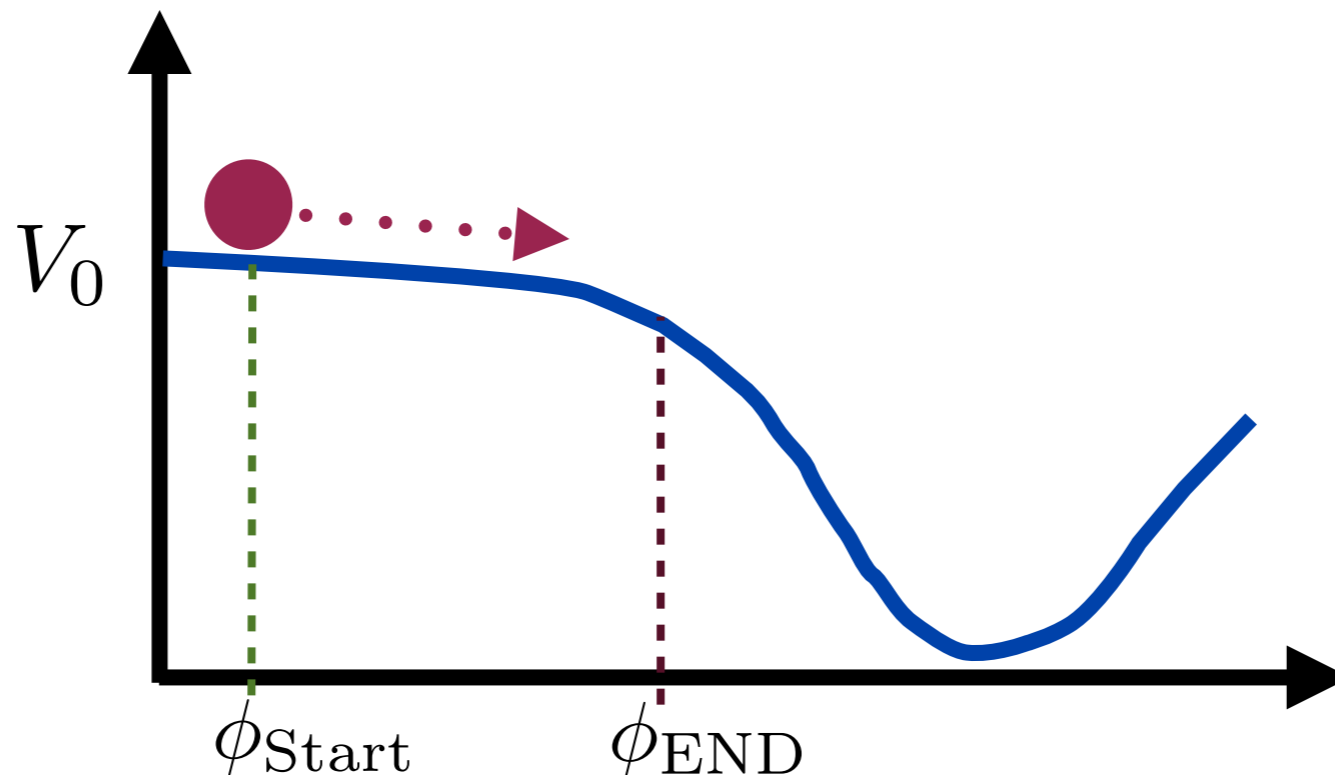
What is the goal?

What are we testing?

Inflation: the conventional picture

A rolling scalar field $\quad \mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$

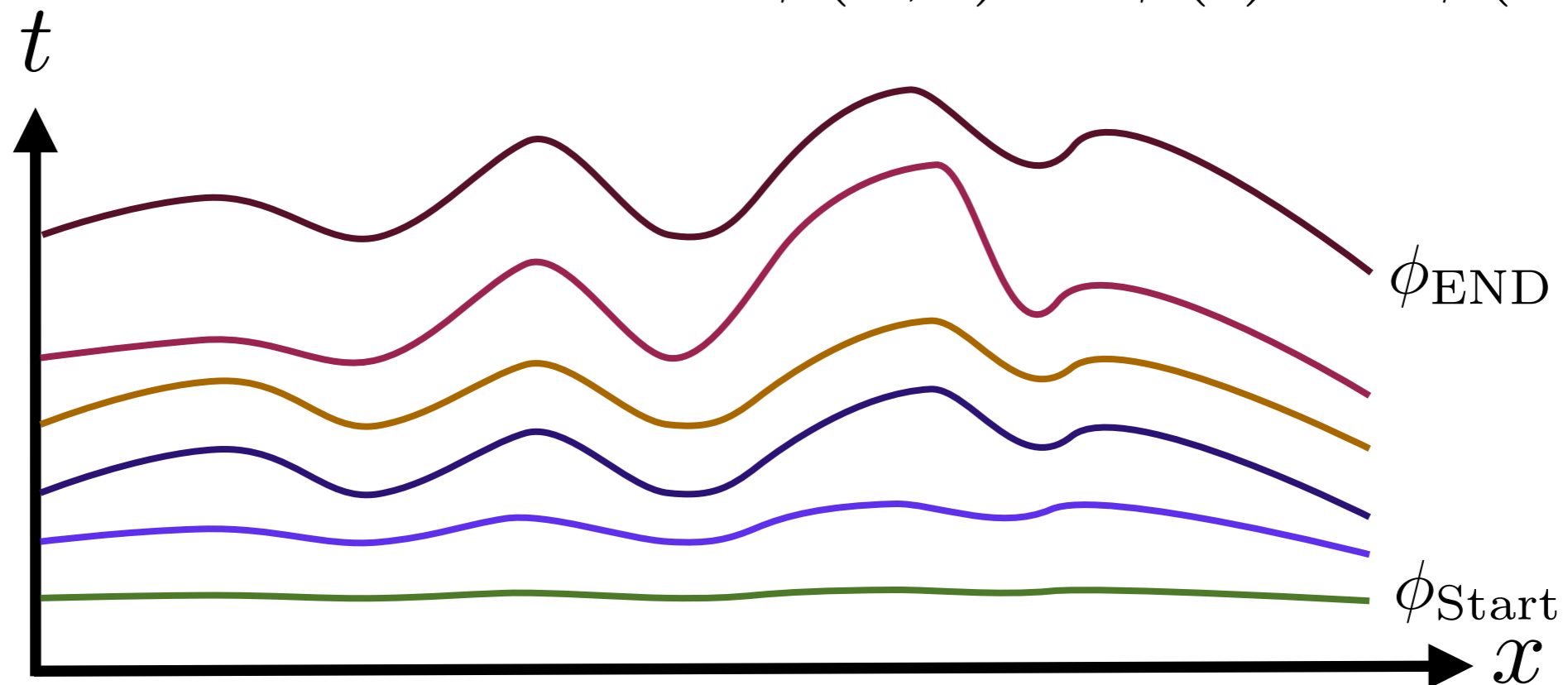$$\phi(t) : \dot{\phi}^2 \ll V(\phi)$$

Perturbations: the conventional picture

The scalar field fluctuates: $\phi(x,t) = \phi(t) + \delta\phi(x,t)$

Source of metric perturbations : $\zeta = \dfrac{\delta a}{a} \sim \dfrac{H\delta\phi}{\dot{\phi}}$

Inflation: a modern view

There are lots of mechanisms beyond slow-roll

Armendáriz-Picón et al., Silverstein & Tong; Alishahiha et al.; ...

They have two things in common:

(1) Near de Sitter geometry : $H^2 \gg |\dot{H}|$

(2) A clock that defines "end of inflation"

"clock" = Spontaneously broken time-translations

Does not require a scalar field (in principle)

Inflation

Perturbations: a modern view

Fluctuations describe goldstone boson π

$$\mathcal{L}_\pi = F(t + \pi, \nabla^\mu, g^{\mu\nu})$$

Creminelli et al.
Cheung et al.

Effective field theory (EFT) of inflation

Goldstone describes fluctuations of the clock

Goldstone is "eaten" by the metric: $\zeta = \dfrac{\delta a}{a} = -H\pi$

The Power Spectrum

The power spectrum is controlled by two scales:

(1) Scale of symmetry breaking: f_π^2

e.g. for slow-roll: $f_\pi^2 = \dot{\phi}$

(2) Hubble scale (H): energy scale of fluctuations

$$\langle H^2 \pi^2 \rangle \sim (4\pi^2)\Delta_\zeta^2 = \frac{H^4}{f_\pi^4}$$

$$\Delta_\zeta^2 = 2.2 \times 10^{-9}$$

The Power Spectrum

The power spectrum is controlled by two scales:

$$f_\pi = 57H$$

$$(2\pi)\Delta_\zeta = \left(\frac{H}{f_\pi}\right)^2$$

$$H_{\mathrm{inflation}}$$

Non-Gaussanity

Effective action for goldstone contains interactions:

$$S_\pi^{\text{int}} = \int d^4 x \sqrt{-g} \left[M_2^4 \left(\dot{\pi}^3 - \dot{\pi} \frac{(\partial_i \pi)^2}{a^2} \right) + M_3^4 \dot{\pi}^3 + ... \right]$$

Interactions give rise to non-Gaussian correlators

These coefficients are model dependent

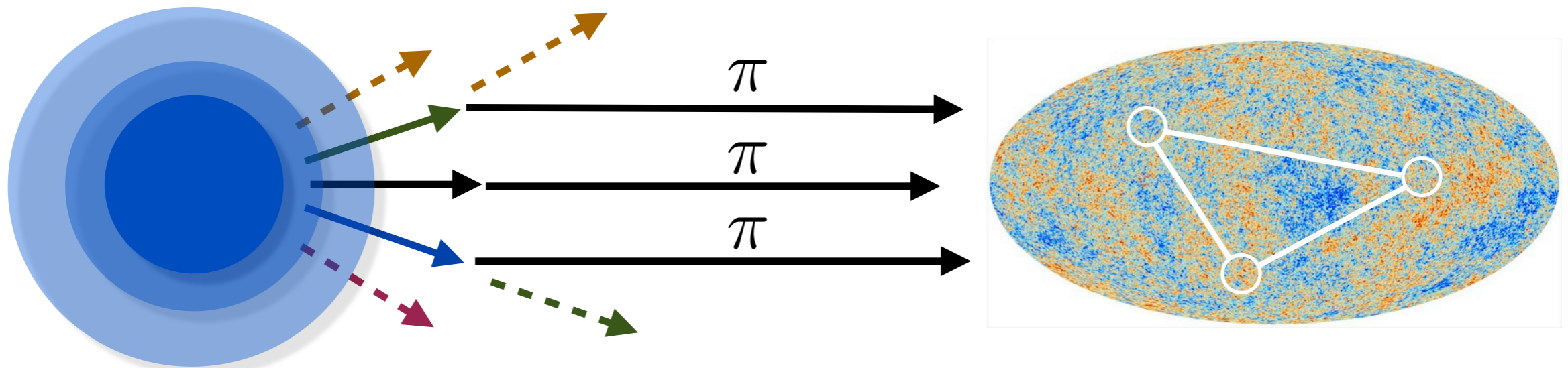Gaussian correlation functions as $H \to 0$
    (holding the coefficients fixed)

Non-Gaussanity

Goldstone can also interact with other fields:

$$S^{\mathrm{mix}} = \int d^4x \sqrt{-g}\left[(-2\dot{\pi} + \partial_\mu\pi\partial^\mu\pi)\mathcal{O} + \dots\right]$$

Senatore & Zaldarriaga, Chen & Wang, Baumann & DG, …

All field with $m \lesssim H$ are excited during inflation

We observe the "decays to π"

Non-Gaussanity

What is the point?

Non-Gaussanity tests particle physics at the scale H

Probes self-interactions of the "inflaton"

Sensitive to any extra degrees of freedom
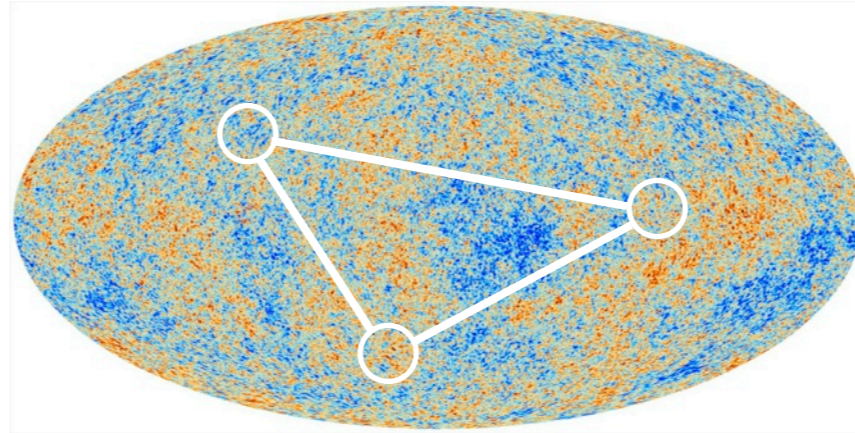(e.g. we can test for SUSY at these scales) Baumann & DG

This can be a very high scale: $H \lesssim 10^{14}\,\mathrm{GeV}$

Limits after Planck

Most constraints are on the 3-point function
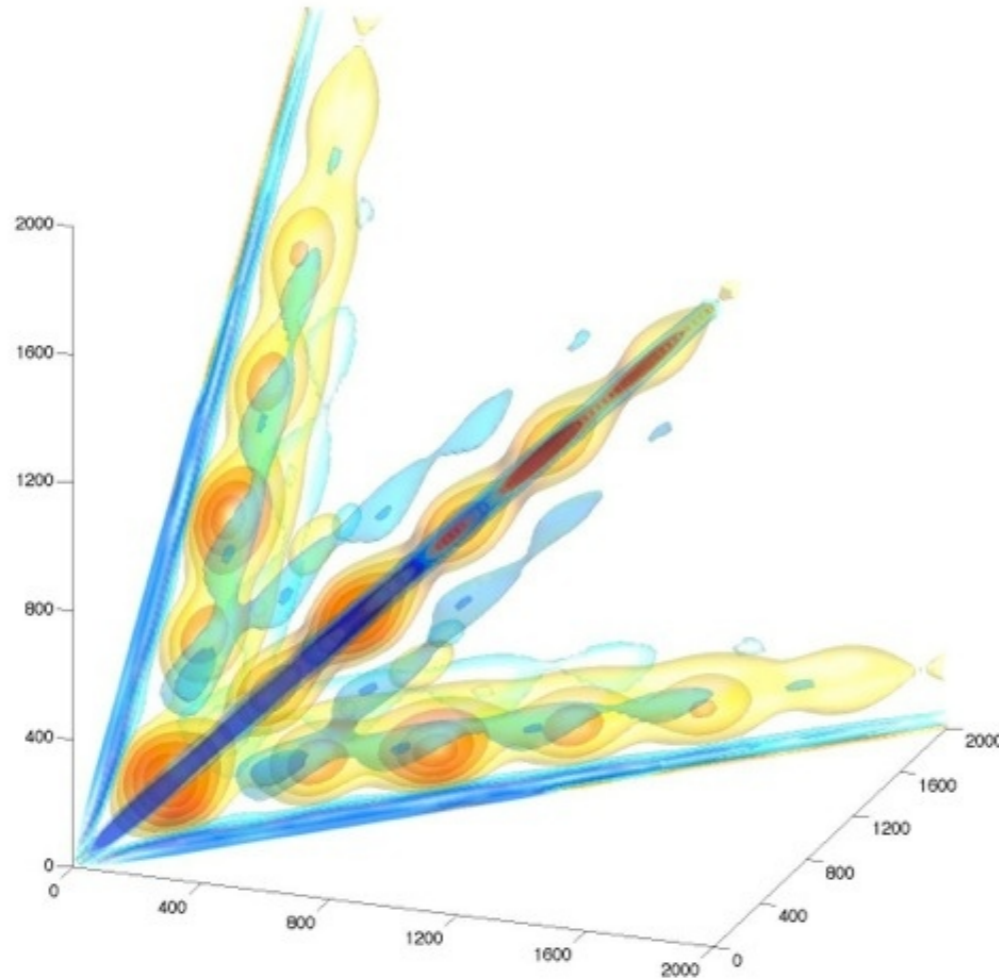

Constraint given in terms of individual templates

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle = B(k_1, k_2, k_3)(2\pi)^2 \delta^3(\mathbf{k}_1 + \mathbf{k_2} + \mathbf{k}_3)$$

For a given template, bound $f_{\rm NL} \equiv \dfrac{5}{18} \dfrac{B(k,k,k)}{P_\zeta(k)^2}$

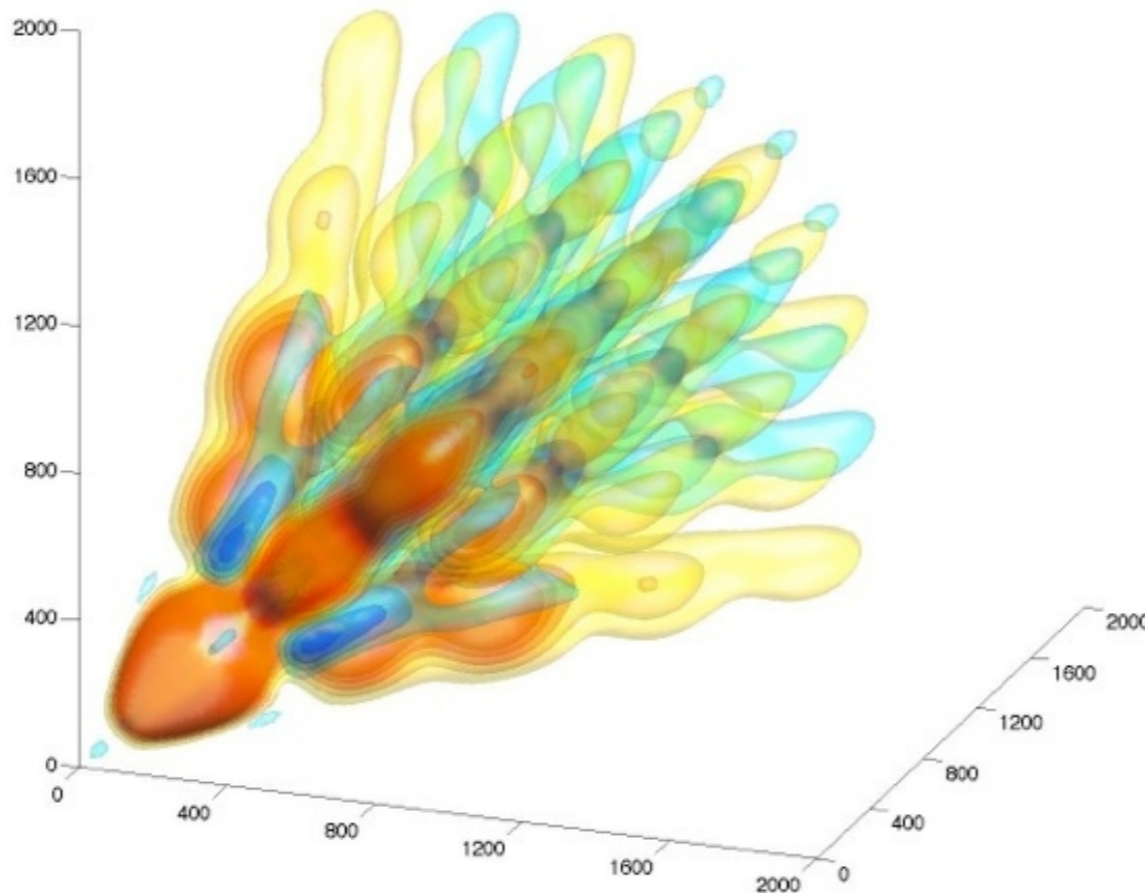With this definition: non-gaussian = $f_{\rm NL} \sim 10^5$

Planck reports limits on 3 templates:

Peaked at:
$$k_1 \ll k_2 \sim k_3$$

$$f_{\text{NL}}^{\text{local}} = 2.7 \pm 5.8 \quad (68\% \text{ C.I.})$$

Courtesy of Fergusson & Shellard
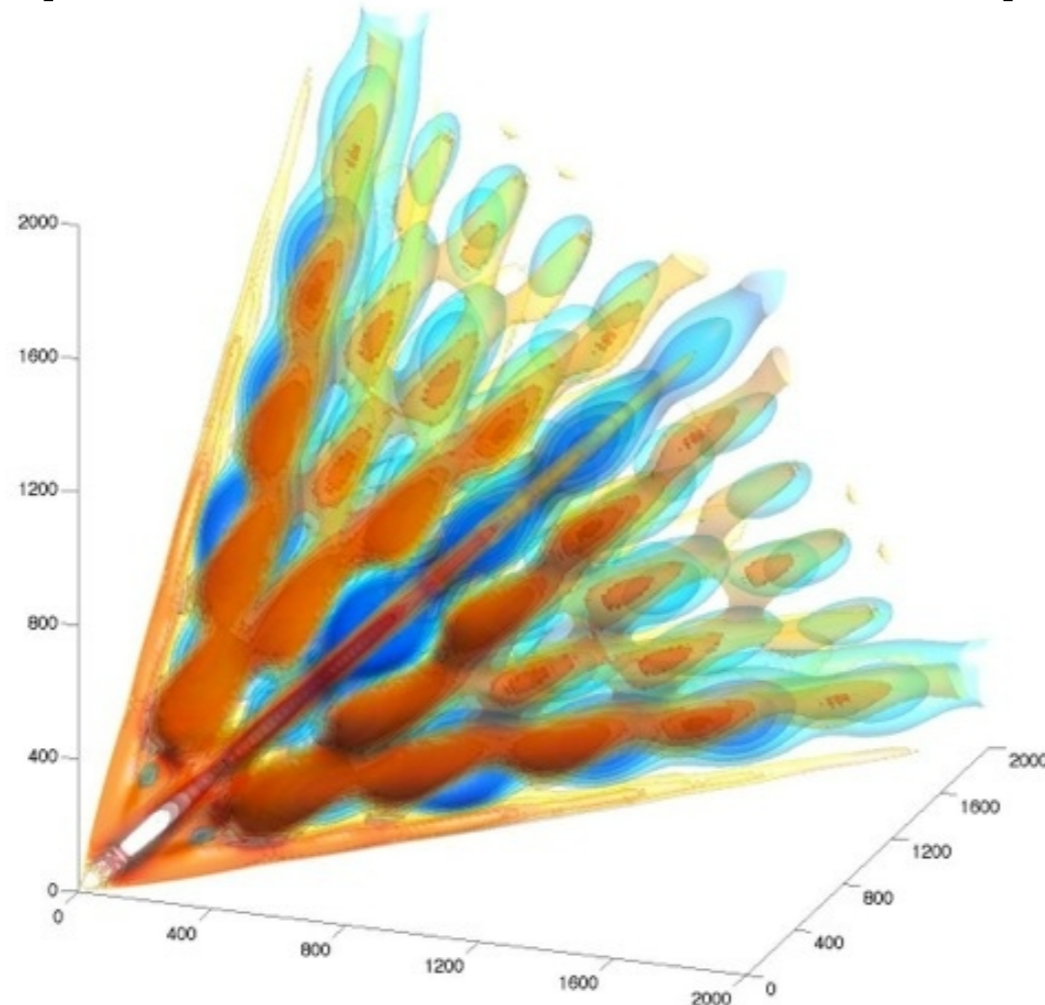
Planck Bounds

Planck reports limits on 3 templates:

Peaked at:
$$k_1 = k_2 = k_3$$

$$f_{\mathrm{NL}}^{\mathrm{equil}} = -42 \pm 75 \quad (68\% \ \text{C.I.})$$

Planck reports limits on 3 templates:

Peaked at:
$$k_1 = k_2 = k_3$$
&
$$k_1 = k_2 = \frac{1}{2}k_3$$

$$f_{\mathrm{NL}}^{\mathrm{ortho}} = -25 \pm 39 \ (68\% \ \mathsf{C.I.})$$

Planck Bounds

Common sentiments:

'Bounds on NG (strongly?) favor a simple mechanism'

'Data has ruled out exotic models'

Are these statements true?

Is there a model-independent expectation for the size of NG in non-slow roll models?

Implications for Inflation

Single–Field Inflation

In single–field Inflation:

NG constrains self–interactions of π

Soft pion theorems: $f_{\mathrm{NL}}^{\mathrm{local}} = 0$ Maldacena; Creminelli & Zaldarriaga

(aka consistency condition)

Use other bounds like precision electroweak tests

I.e. Bound scale of "new physics" $\mathcal{L} \supset \dfrac{1}{\Lambda^2} \dot{\pi}_c^3$

Constrain energy of interactions: $\mathcal{L} \supset \dfrac{1}{\Lambda^{\Delta-4}} \mathcal{O}_\Delta$

Energy

Background

$f_\pi = 57H$

EFT of Inflation — — — — — — — — Λ ??

$H_{\text{inflation}}$

Freeze-out

The primary constraint comes from equilateral:

$$\mathcal{L}_3 \supset \qquad \frac{1}{\Lambda_1^2}\dot{\pi}_c \frac{(\tilde{\partial}\pi_c)^2}{a^2} \qquad\qquad \frac{1}{\Lambda_2^2}\dot{\pi}_c^3$$

$$f_{\mathrm{NL}}^{\mathrm{equil.}} \qquad \frac{85}{324}(2\pi\Delta_\zeta)^{-1}\frac{H^2}{\Lambda_1^2} \qquad \frac{20}{729}(2\pi\Delta_\zeta)^{-1}\frac{H^2}{\Lambda_2^2}$$

Planck (68 %) $\qquad \Lambda_1 \gtrsim 3.5\,H \qquad\qquad \Lambda_2 \gtrsim 1.1\,H$

Single-Field Inflation

The primary constraint comes from equilateral:

$$\mathcal{L}_3 \supset \qquad \frac{c_1}{f_\pi^2}\dot{\pi}_c\frac{(\tilde{\partial}\pi_c)^2}{a^2} \qquad\qquad \frac{c_2}{f_\pi^2}\dot{\pi}_c^3$$

$$f_{\mathrm{NL}}^{\mathrm{equil.}} \qquad\qquad \frac{85}{324}c_1 \qquad\qquad \frac{20}{729}c_2$$

Planck (68%) $\qquad c_1 = 30 \pm 280 \qquad\qquad c_2 = 690 \pm 2100$

Places lower bound on "strong coupling scale"

Energy

Background

Strong Coupling

$$f_\pi = 57H$$

$$\sqrt{4\pi}\Lambda_{1,2} \gtrsim (4-12)\,H$$

$$H_{\text{inflation}}$$

Freeze–out

Single-Field Slow-Roll

What would we expect from slow roll ?

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \frac{1}{\Lambda^4}(\partial_\mu\phi\partial^\mu\phi)^2$$

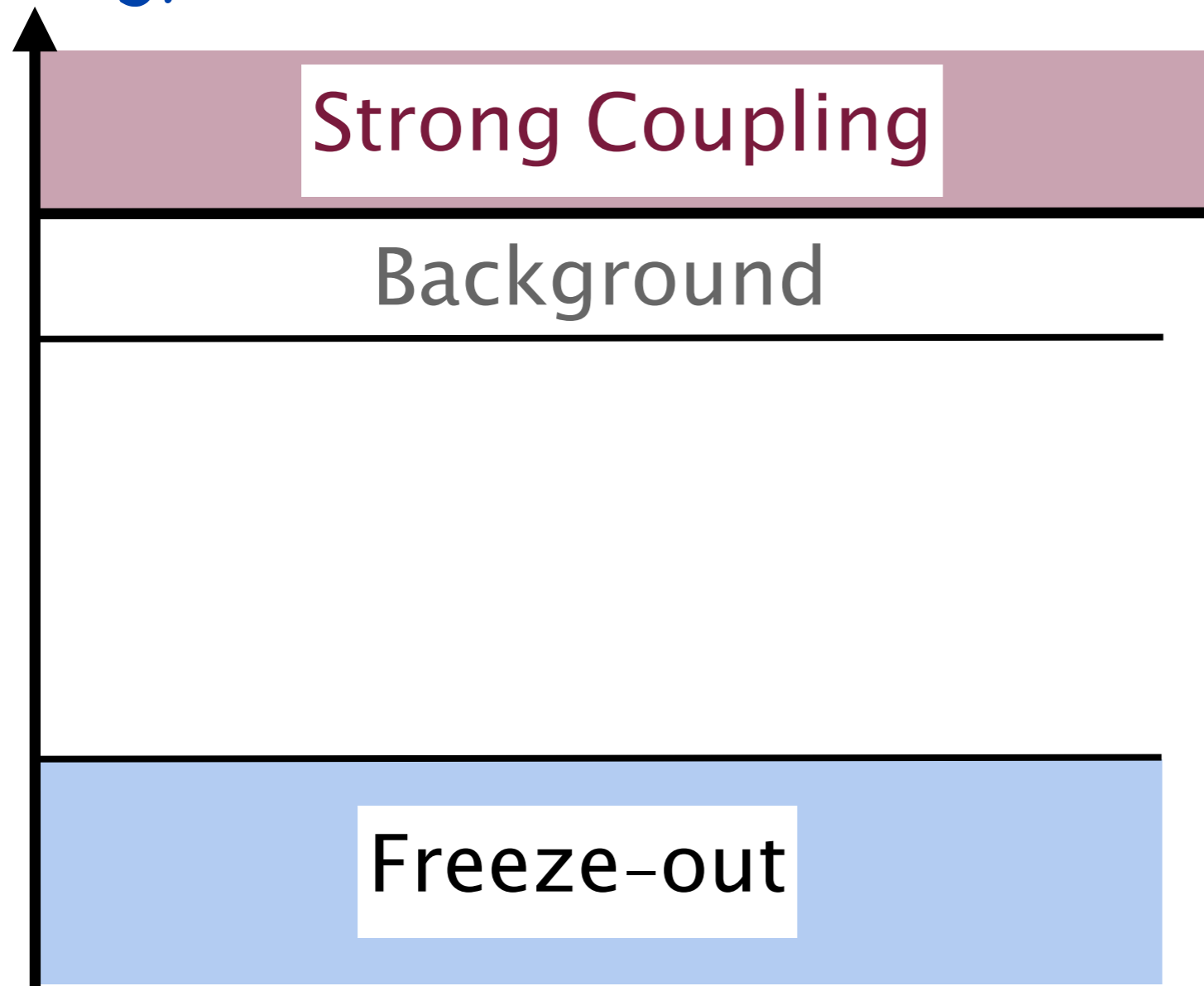For this to be slow-roll: $\Lambda^2 > \dot{\phi}$

In slow-roll, we have a bound on equilateral

$$f_{\mathrm{NL}}^{\mathrm{equil.}} = \frac{\dot{\phi}^2}{\Lambda^4} < 1$$

Single-Field Slow-Roll

What would we expect from slow roll ?

Energy

Strong Coupling

Background

Freeze-out

$$\Lambda > \dot{\phi}^{1/2}$$
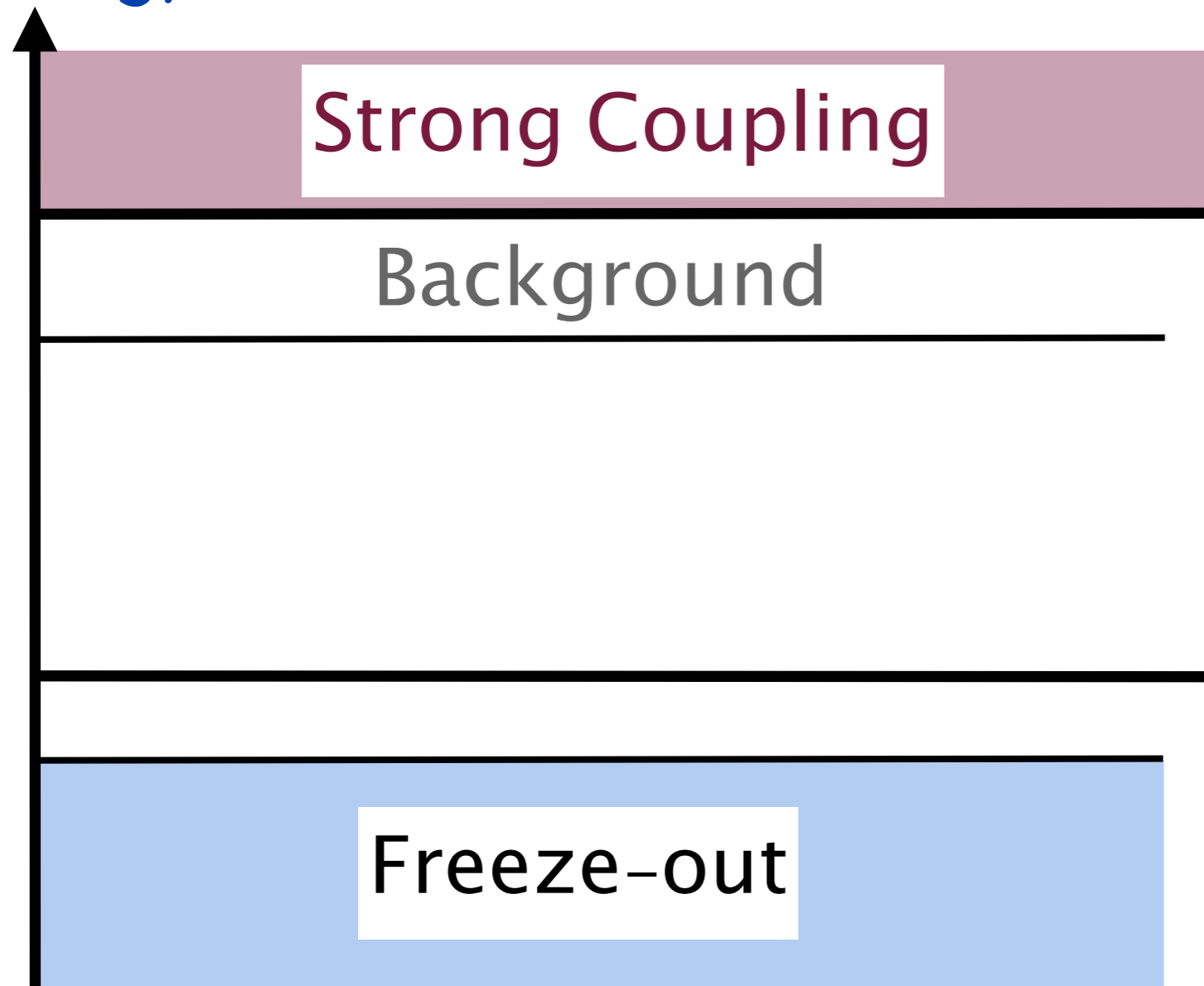
$$\dot{\phi}^{1/2} = 57H$$

$$H_{\text{inflation}}$$

Long way to go before data suggests slow–roll

Energy

Strong Coupling

Background

$\Lambda_{1,2} > f_\pi$

Requires order
10–100 improvement

$\sqrt{4\pi}\Lambda_{1,2} \gtrsim (4-12)\,H$

Freeze–out

Multi–field Inflation

Planck constraints still have teeth:
Strong bounds on mixing between sectors

E.g. from slow–roll we might have

$$\mathcal{L} \supset \frac{1}{\Lambda}(\partial_\mu \phi \partial^\mu \phi)\sigma$$

Planck bounds from local shape ($f_{\mathrm{NL}}^{\mathrm{local}}$):

$$\Lambda \gtrsim 5 \times 10^4\, H$$

DG et al.;
Assassi et al.

Multi–field Inflation

Planck constraints still have teeth:
Strong bounds on mixing between sectors

E.g. from slow–roll we might have

$$\mathcal{L} \supset \frac{1}{\Lambda}(\partial_\mu \phi \partial^\mu \phi)\sigma$$

Planck bounds from local shape ($f_{\mathrm{NL}}^{\mathrm{local}}$):

$$\Lambda \gtrsim 0.5 \left(\frac{r}{0.01}\right)^{1/2} M_{\mathrm{pl}}$$

DG et al.;
Assassi et al.

Generalization

Limits on NG bound couplings between sectors

$$\mathcal{L} \supset \frac{1}{\Lambda^\Delta} (\partial_\mu \phi \partial^\mu \phi) \mathcal{O}_\Delta$$

For moderately NG hidden sectors

$$\Lambda \gtrsim (10^5)^{1/\Delta} H$$

Origin of the constraint largely insensitive to details

Related to single field bounds when $\Delta \gtrsim 4$

What is the Goal?

What is the Goal?

Back to the sentiments:

'Bounds on NG (strongly?) favor a simple mechanism'
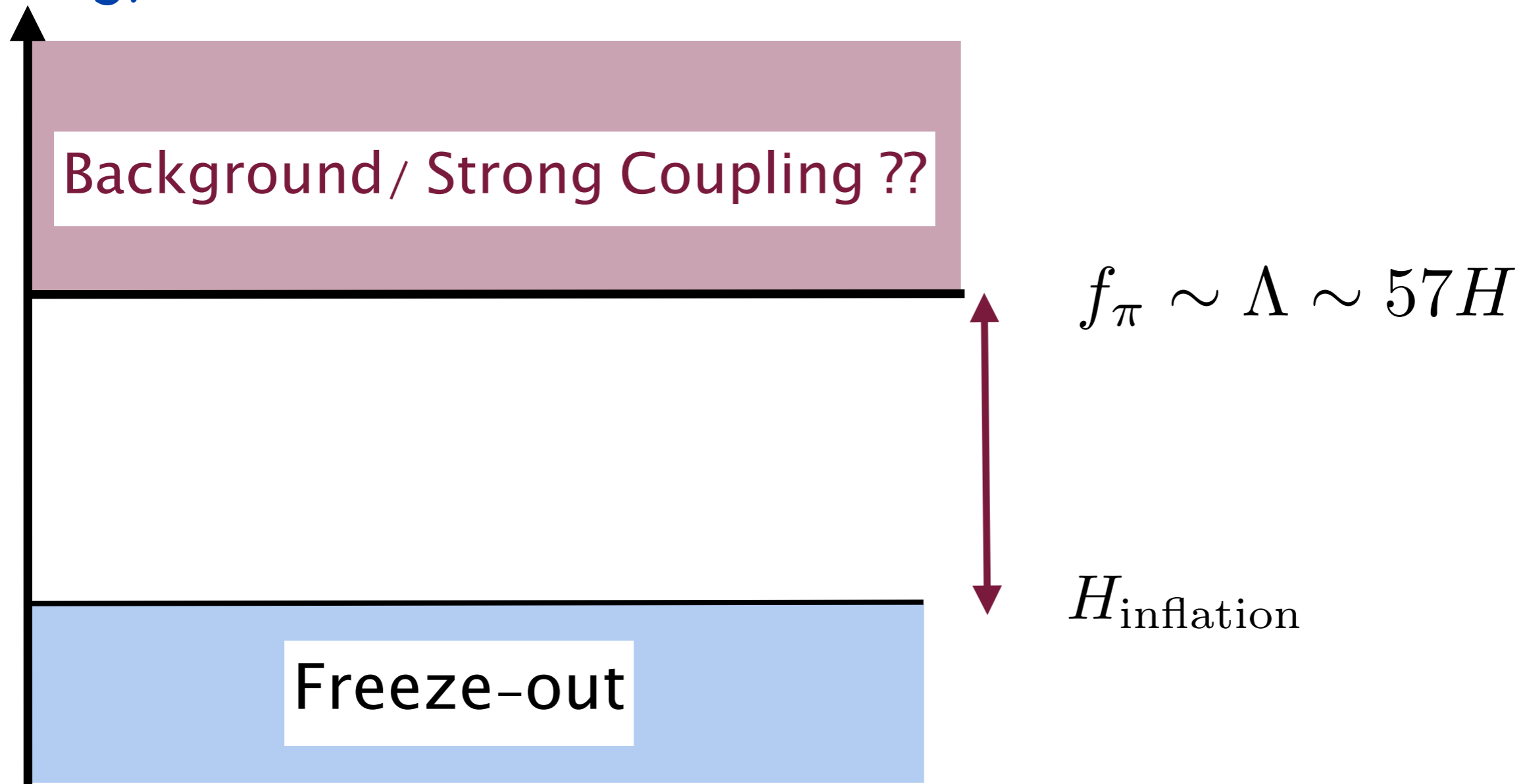
'Data has ruled out exotic models'

It seems (to me) like there is a big window left

Can we think of something "exotic" ?

What is the Goal?

Could Inflation be due to strong dynamics?

Energy

Background / Strong Coupling ??

$$f_\pi \sim \Lambda \sim 57H$$

$$H_{\text{inflation}}$$

Freeze-out

What is the Goal?

Could Inflation be due to strong dynamics?

i.e. Is there an analogue of technicolor (or QCD)?

Time translation broken by composite operator

$$\langle \mathcal{O} \rangle = f_\pi^{\Delta+1} \times t$$

If the only scale is f_π, we might expect

$$\mathcal{L} \supset \frac{\mathcal{O}(1-10)}{f_\pi^2} \dot{\pi}(\partial \pi)^2 \longrightarrow f_{\mathrm{NL}}^{\mathrm{equil.}} \lesssim 5 \quad \textbf{??}$$

$$(\Delta f_{\mathrm{NL}}^{\mathrm{equil.}})_{\mathrm{Planck}} = 75$$

Here are some goals:

Single-field slow-roll is ruled out for

$$f_{\mathrm{NL}}^{\mathrm{equil.}} > 1$$

A null result at this level would be <u>very</u> informative
(A detection would be spectacular!)

Single field is ruled out with any detection of

$$f_{\mathrm{NL}}^{\mathrm{local}} > 0$$

Always useful to improve these bounds

Summary

Non–Gaussanity is high energy particle physics

Tests particles and interactions at $H \lesssim 10^{14}\,\mathrm{GeV}$

Well defined threshold exists for equilateral:

$$f_{\mathrm{NL}}^{\mathrm{equil.}} \sim 1$$

Requires a measurement of the bispectrum in LSS
(much more work is needed but the data will be there!)